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Islanding of Distribution Networks: Challenges and Potential Solutions

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***Abstract*— The concept of generating electricity from renewable sources has been developed to solve the problems raised by environmental pollution and diminishing fossil fuel resources. Integration of clean renewable generation into existing electrical systems has been proven to benefit both power system operators and customers. However, a number of technical and economic challenges still exist with regards to effective integration and optimal utilization of such sources. One of the issues much debated recently is the provision for islanded operation in distribution networks utilizing the locally available generation. There are many obstacles and challenges concerning technical, economic and regulatory aspects of islanded operation which attract a significant amount of research worldwide. This review paper covers the state-of-the-art in research on islanded systems, specifically concerning: generation control, islanding detection, protection, and other functions such as power-sharing and black start capability.**

Keywords—Islanding, distribution generation, detection, protection, power-sharing, black start

I. INTRODUCTION

Nowadays, as the electricity demand increases and the power system expands rapidly, causing the depletion of conventional, fossil fuel based energy resources, and thus, the environmental pollution has become a major concern. In UK, as estimated by National Grid, an increase of approximately 1 GW/year for the peak time electricity demand could happen in a wealthy society after 2030, and the electricity peak demand could reach 85 GW in 2050, compared to about 60 GW today [1]. In order to meet the Paris agreement targets for holding the increase in global temperatures to below 2 °C above pre-industrial levels, and 80% carbon reduction target (compared to 1990 levels) by 2050, several effective solutions have been developed and one of which is to integrate Renewable Energy Sources (RESs) into the utility grid and develop a range of Distributed Generation (DG) technologies. The DGs can achieve enhanced flexibility and security, along with decreased peak demand, reserve margin, and transmission network losses [2].

Fig. 1 illustrates the future trends of decentralized generation installations in the UK across four scenarios. The power generation from coal is anticipated to drop to zero by 2050; meanwhile, the participation of gas-based generation is expected to drop considerably in all scenarios. Other renewable technologies are expected to continue their significant growth, although the rate of growth will depend on a number of technological and economic factors.

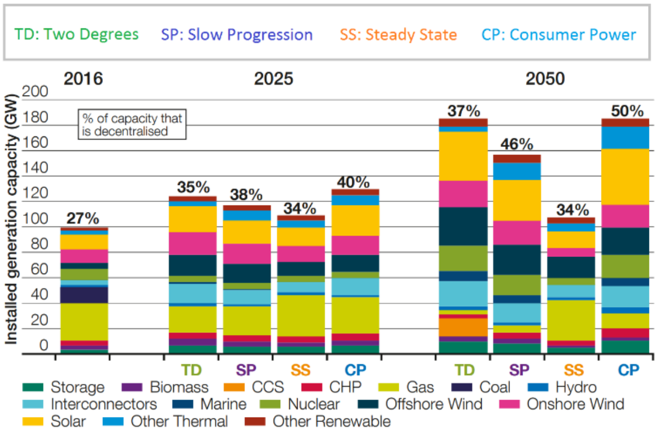

Fig. 1. Generation capacity by type and proportion of decentralized generation [1]

However, due to the intermittency and non-dispatchable characteristics of RESs, especially wind and solar energy, and the complexity and security constraints resulting from the integration of DGs, there is a potential for harmful effects on grid performance, reliability and power quality, if such sources are connected directly to the utility grid. Besides, the integration of RESs brings several economic challenges. For instance, the clean and inexpensive characteristics of RESs can lead to recession of electricity market, intermittency and fluctuation of RESs cause an increased demand for automatic response systems and ancillary services, as well as demand-side response [3]. Therefore, the concept of self-sufficient subsystem utilizing local available generation (often termed as microgrid) has been proposed to act as an interface between the RESs and the main grid. Figure 2 demonstrates a typical microgrid architecture including several RES technologies.

Generally, the DG distribution systems (or the microgrids) can operate in either grid-connected or islanded mode. These two modes require different operating principles, including different control strategy and protection. In grid-connected mode, the DG systems are designed to generate maximum power to the main grid and they typically operate in constant power or constant current mode.

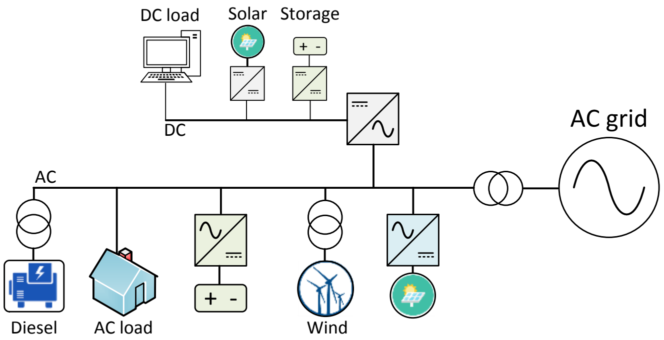

Fig. 2. DG system with RESs

However, when the microgrid is isolated from the main grid (e.g. following a fault) it operates in an islanded mode. In this mode, the DG systems should be capable of detecting the islanding situations and switch to frequency and voltage control mode in order to provide the correct amount of power to the local loads and maintain constant frequency and voltage [4].

The remainder of the paper is structured as follows: Section II reviews the control techniques for DG systems in different operating modes and seamless transition strategies between the modes; Section III presents the islanding detection challenges and existing techniques; in Section IV, islanded system protection issues and challenges are outlined, including newly-developed approaches, and future trends; finally, other related topics such as power-sharing and black start capability raised by islanding are introduced in Section V.

II. OPERATION & CONTROL OF DG NETWORKS

A. *Control Techniques in Different Modes*

As aforementioned, the DG systems can operate in both grid-connected and islanded modes. As concluded in [5], different control techniques are applied to each mode of operation, as summarised below.

1) *Grid-connected Mode*

In this mode, the control approaches can be classified depending on the existence and utilization of the communication link.

For control techniques without communication links, the droop control is one of the most common choices [5]. It can achieve a high reliability, but it suffers from the trade-off between the output voltage regulation and the power-sharing accuracy, reduced transient response, and loss of mains synchronization.

The control techniques with communication links consist of distributed, one cycle, and active and reactive power control which can be further classified into three methods: direct power, inverter flux, and current control [5]. The advantage of these control techniques is the enhanced system performance such as simplicity and fast dynamic response by the aid of the internet, microwave, etc., whereas the disadvantage is the reduced distributed and redundant level caused by the wires which limit the location of the inverter units and produce noise.

2) *Islanded Mode*

In this mode, the control is classified as either single or parallel operation.

The single operation includes deadbeat, perfect robust servomechanism problem, and advanced control [5]. The strengths embrace a fast-transient response with low Total Harmonic Distortion (THD) at a lower sampling frequency, exclusion of unexpected voltage harmonics, and quick recovery from load transient.

The parallel operation can be further classified into two methods: the methods with and without communication links. The methods with communication links include distributed, combined, current distribution, and advanced control; whereas the methods without communication link include droop and modified droop control [5]. This operation enjoys expandable power, reliability, and redundancy, but sacrifices load equally which needs additional current sharing control.

B. *Seamless Transition between Modes*

Furthermore, there is another concern which is related to the islanding operation of DG systems, i.e. seamless transition between modes. In accordance with IEEE Std. 1547.4-2011, the operation modes of a microgrid are strictly classified into four: area EPS (electric power system)-connected, transition-to-island, island, and reconnection mode, respectively [6]. The operational principles and control schemes are designed specifically for DG systems in grid-connected and islanded modes. Hence, when the operation mode changes, the DG needs to alternate the operational principles and control schemes correspondingly, which can potentially cause disruption, transients, high voltage and current spikes during the transition period [7]. Therefore, seamless control strategies need to be developed. In literature, according to [8], a passive detection algorithm and a load shedding algorithm are designed to switch during transition-to-island mode, whereas a recloser algorithm and a synchronization algorithm are designed to switch during reconnection mode. In [7], a stationary (α-β) reference frame and a unified control scheme are developed to perform in both major modes so that the specific control schemes for DG systems in different modes and voltage or current spikes can be avoided during the transition periods.

III. ISLANDING DETECTION

One of the challenges that the penetration of DG systems encounters is the islanding detection. It is known that the conventional power systems comprise of large synchronous generators which have a fairly large inertia. However, such synchronous generators are gradually replaced by modern inverter-connected distribution generation units. As such, any large kinetic energy is decoupled from the network resulting in a low inertia. When large transients occur in low-inertia networks, voltage and frequency are expected to deviate significantly from nominal values, which affects the common anti-islanding methods such as Rate of Change of Frequency (RoCoF) and Vector Shift (VS), and the performance of islanding detection methods [9] [10].

Therefore, the islanding detection is important to the power system, and this situation should be detected in time in no matter what operation mode. Precisely, in grid-connected mode, real-time monitoring and forecast methods should be applied so that once the islanding is detected, action of disconnecting can be taken in time; in islanded mode, the detection methods are also desired so as to inform the DG systems to change the operational principles and control schemes in advance if no seamless transition control strategies are equipped.

As [11] [12] concluded, islanding detection techniques can be classified into two types, remote and local techniques, and the local techniques can be further classified into passive, active and hybrid methods.

A. Remote Islanding Detection

This detection relies on communication between main grid and DGs, and examples of this detection contain transfer trip and power line signaling scheme [12]. The transfer trip scheme is based on monitoring the status of all circuit breakers and reclosers which are able to trigger islanding, whereas the monitor can be achieved by Supervisory Control and Data Acquisition (SCADA) [12]. The power line signaling scheme is based on consistent signal broadcast through power lines by the signal generator at the transmission system so that once the signal receivers equipped with the DGs cannot detect any signal, then the DG units will trip immediately [12] [13]. The remote islanding detection owns a high reliability, but the implementation is costly.

B. Local Islanding Detection

The passive detection method is based on measuring system parameters like voltage, frequency, and harmonic distortion, and the thresholds set for these parameters are different in islanded and grid-connected mode [12]. Common examples include the rate of change of output power, the rate of change of frequency, the rate of change of frequency over power, change of impedance, voltage unbalance, harmonic distortion [12].

Although the passive detection method is simple, rapid, and disturbances avoidable, it is hard to detect the islanding when the load and generation are perfectly matched [11] [12]. Hence the active detection method is developed to eliminate these restrictions. This method introduces perturbations to the power system which is able to cause a significant change in system parameters during islanded mode, rather than moderate change during grid-connected mode [12]. Common examples include reactive power export error, impedance measurement, phase (or frequency) shift, active frequency drift with positive feedback method [12].

The hybrid detection methods take advantages of both passive and active methods, whereas the active method is only operated when the islanding is sensed by the passive method [12]. Common examples include positive feedback and voltage imbalance-based, voltage and reactive power shift-based techniques [12].

IV. PROTECTION

There are many challenges in the design of power system protection when an increasing number of DGs, especially the power electronics-interfaced sources, are connected to the distribution network. It is known that most of the conventional distribution level protection schemes rely on unidirectional short-circuit current flow in the predominantly radial distribution system. The integration of DGs disturbs this order and results in a complicated system with multiple sources and bidirectional fault current flows [14]. Besides, even in conventional radial architectures the presence of DGs can cause conventional protection scheme blinding, false tripping, and/or recloser problems [14].

If distribution system islanding was to become a common practice, the protection schemes would need to respond to the faults occurring in both grid-connected and islanded mode. In grid-connected mode, both utility grid and microgrid contribute to the fault currents, and the protection schemes should be able to isolate the DG systems, or the microgrid from the utility grid without unnecessary delays; whereas, in islanded mode, only the DG systems produce the fault currents, and the protection schemes only disconnect the smallest part inside the microgrid to clear the faults [15] [16] [17]. In addition, the magnitude of the fault current in the islanded mode can be very low (e.g. less than twice the rated current) due to the low thermal capability of the semiconductor switches [18]. This phenomenon results in the situation when the protective relays respond slowly to the faults, or in the worst case scenario, not detecting the faults. Therefore, the ability to operate in dual-mode is crucial for future protection schemes.

So far, there are several other protection-related problems which have not been resolved yet. These include the changes in the magnitude and direction of fault current, reduced fault detection sensitivity and speed (especially with tapped connection of Distributed Energy Resources - DER), unnecessary tripping of utility breakers when the fault happens on neighbouring lines (sympathetic tripping), as well as a risk of fault levels exceeding the capacity of the existing switchgear [19]. Grounding is also an essential concern, especially for hybrid AC/DC microgrids. The appropriate grounding point in the network should be chosen to ensure secure detection of earth faults [15].

A good protection scheme is required to overcome the “3S” challenge: namely sensitivity, selectivity, and speed [19]. Many protection approaches have been put forwarded in literature. In [19] it is indicated that many conventional protective approaches like overcurrent protection, distance protection, differential protection, and adaptive protection can be applied if they meet special technical requirements including utilization of digital directional overcurrent relays, new/existing communication infrastructure and standard communication protocols. In [20], Fault Current Limiters (FCLs) and Unidirectional Fault Current Limiters (UFCLs) are summarized which aim to prevent the coordination protection problems between upstream and downstream overcurrent relays. In [14], differential protection and Wide Area Protection (WAP) are presented, both of which are based on communication techniques. In [17], standardization and self-healing actions are illustrated, the former aiming to achieve a high cooperation among different components of the grid, and the latter including reconfiguration, load shedding, and control of dispatchable generators’ output powers. In [16], besides overcurrent relays and reclosers, Sectionalising Circuit Breakers (SCBs), Miniature Circuit Breakers (MCBs), and fuses can also be applied in AC distribution network protection. In [18], several solutions are introduced including pattern recognition, harmonics content-based, wavelet transform-based, and traveling wave-based schemes. In [21], an innovative ensemble classifier system, which uses a set of classifiers to provide a single output accumulated and integrated from outputs generated by each classifier, is developed for PV and synchronous DG integrated microgrids which is able to achieve mode detection, fault detection/classification, section identification and location estimation. In [22], a protection coordination scheme for distribution networks with high penetration of PVs is presented using two strategies: modified characteristic curve and output current limiting. This proposed approach avoids PV's output power reduction and the utilization of communication links. Overall, the choice of protection is based on network characteristics and cost [11].

For future development of the microgrid protection, there are also some new trends. For example, as [17] expected, in a smart grid, the communication and information infrastructures can be classified into three domains: Wide Area Network (WAN), Neighbourhood Area Network (NAN), and Home Area Network (HAN); the future protection systems are able to cooperate effectively with control systems under communication and information infrastructures in hybrid AC/DC microgrids; some novel protective and control devices can be applied to the power network, such as Solid-State Transformer (SST), which is a high power converter, designed to benefit from power flow control, voltage sag compensation, and fault current limitation. Another device is a Z-source circuit breaker, which applies a z-source LC circuit at medium-voltage dc power systems to provide a thyristor zero current crossing, aiming to switch off automatically in Silicon Circuit Rectifier (SCR) in response to a fault [23].

V. FURTHER CONSIDERATIONS

There are other issues raised by islanding operation which need to be considered, such as power-sharing and black start capability. Once the DG systems are isolated from the main grid, every DG unit must supply its share of the load in line with its rating [24]. However, there still exist many problems in achieving accurate and stable power-sharing control.

If a failure happens during the transition to desired operation mode, black start sequence is required. As IEEE Std. 1547.4-2011 defines, the black start is "the ability to start local generation with no external source of power" [25]. The black start is mostly utilized after a severe electric failure, such as a blackout. The blackout can adversely affect economic development, traffic, and people's daily life. The worst power blackout recorded in the world occurred in India in 2012. The system took 16 hours to be partially recovered and almost 600 million citizens were influenced [26]. Therefore, an effective black start strategy is required so as to reduce the interruption time and economic losses.

A. Power-sharing Control

As outlined in [9], two main power-sharing techniques are implemented, namely communication-based and droop characteristic-based control.

1) Communication-based Control

Communication-based control can achieve appropriate voltage regulation and power sharing. Nevertheless, this control needs communication lines which increases the cost. There are three typical control techniques, namely concentrated, master/slave, and distributed control [9].

The concentrated control uses common synchronization signals, current sharing blocks, and Phase Locked Loop (PLL) circuits. This control aims to add current errors acting as compensation components of the voltage reference to every block to reduce the difference among output currents, and it can be applied in both steady state and transients.

The master/slave control applies parallel control method, whereas the starting block performs as the master inverter, and others act as slave inverters. This control performs well in steady state; however, there is no inbuilt redundancy against the failure of the master inverter which results in the failure of the whole system and a high current overshoot in transients.

The distributed control utilizes the instantaneous average current sharing method, which needs a current sharing bus and reference synchronization for the voltage. This control can achieve good voltage regulation and fundamental power sharing, but to avoid degradation of flexibility and redundancy, interconnections between inverters are still needed.

2) Droop Control

The droop characteristic-based control operates without communication so as to avoid the high investment cost and to benefit long-distance connection, but some drawbacks should not be neglected, such as frequency and voltage deviation, harmonic loads, different and unknown line impedances, the fluctuant and changeable output power of DGs. To minimize these effects, several types of droop control techniques are developed, namely conventional droop, virtual structure-based, construct and compensate-based, and hybrid droop/signal-injection-based control [9].

Conventional Droop Control: this control aims to simulate the performance of a synchronous generator to reduce the frequency as the active power increases. It is proven that when the inverter output impedance is highly inductive, the active power relies mainly on the power angle, whereas the reactive power relies mainly on the output voltage amplitude, and this theory can be applied into Voltage Source Inverters (VSIs) by using P/Q droop method. This control holds high expandability, modularity, and flexibility, but it suffers from the slow dynamic response and poor harmonic sharing.

Virtual Structure-based Control: one of the popular techniques, the virtual output impedance loop control, depends on virtual output impedance, and the output inductance can be simulated by drooping the output voltage in proportion to the derivative of the output current over time, which leads to a pure inductance. This control can achieve improved power sharing, eliminate active/reactive power coupling, and system stability; however, the voltage regulation is not fully guaranteed, and differentiation can increase high-frequency noise especially in transients and thus a low pass filter is needed.

Construct and Compensate-based Control: this control is divided into several control techniques. For example, one of the common methods, the adaptive voltage droop control, uses two terms which are built into the conventional reactive power (Q-V) control, one is to compensate for the voltage drop across the transmission lines, the other is to ensure the stability and to improve reactive power sharing in the condition of heavy loading. In general, this control enjoys improved voltage regulation, system stability and power-sharing under heavy loads, unless low bandwidth synchronized communication is added.

Hybrid Droops/Signal-injection-based Control: conventional droop and communication-based control have their own strengths and weaknesses. Therefore, to benefit from advantages of both, a hybrid scheme combining two control techniques has been designed. Furthermore, when a certain harmonic signal including reactive power information is inserted into the output voltage references of each DG unit, an output voltage distortion is generated [24]. In order to reduce this effect and the reactive power error, in the signal-injection-based control, some small disturbance signals including reactive power information are inserted into the frequency reference of every DG unit by applying the active power error [24]. This control can be widely used in linear and nonlinear loads, but it suffers from voltage harmonic distortion.

B. *Black Start Capability*

The success of the black start mainly relies on the installation of storage devices, the operation of Microgrid Central Controller (MGCC) and Microsource Controller (MC), along with the mount of microsources with black start capability [27] [28]. The microsources can be classified into two types, Black-Start Distributed Generation (BSDG) and Nonblack-start Distributed Generation (NBDG) based on whether it possesses black start capability [28]. The BSDGs include gas turbines, hydro units, steam units, and DGs with storage devices like batteries and super-capacitors [29].

There have been various black start procedures developed, and the basic idea is as follows:

- Disconnect all loads;
- Restart the BSDGs to build Low Voltage (LV) network;
- Utilize MCs to control voltage and frequency, and then achieve a synchronization in the partially islanded area;
- Connect controllable loads;
- Connect non-controllable loads and NBDGs when voltage and frequency deviations are eliminated by MCs, and then increase loads gradually to supply power to more areas;
- Synchronise the microgrid with the upstream grid when it is available, and the black start completes.

A number of black start studies have been proposed in the literature. In [29], an optimized black start scheme using a DG with storage devices and V/f control was verified as feasible among different schemes by assessing LV distribution network building time and minimum load power factor. In [30], two methods were proposed to investigate the grid restoration: constantly updated power setpoints and fixed droop. However, each of them has both advantages and disadvantages. Hence, a combined method was developed so that the active power is controlled decentralized by droop control and the reactive power flow is controlled centralized by set points. Besides, to increase the time of islanded operation, an energy management including load shedding and demand-side management was also presented. In [31], a feasible black start procedure was proposed for a microgrid which comprises of BSDGs (e.g. single shaft microturbines and solid oxide fuel cells) and storage devices (e.g. batteries and supercapacitors) and is managed by MGCC. In [28], an effective black start strategy for microgrid with PV and hybrid energy storage systems based on a serial restoration approach was illustrated, where the lithium storage system was chosen to perform as the main power supply, and the Vanadium Redox Flow Battery (VRB) system was chosen to perform as BSDG. In [32], the hydro power plant was found that it has the least black start power requirement which its start-up power is only 0.5-1.0% of its generation rating, hence it was chosen to serve as the BSDG installed near the thermal units in a proposed strategy so as to reduce the restoration time. An alternative approach is shown in [33], where a generator start-up optimization strategy is developed by treating a whole microgrid, including different types of RESs, as a black-start resource and it achieves a good power system restoration. In [34], a novel black start procedure was presented by applying a diesel engine driven synchronous generator, a wind turbine generator and an energy storage system in a microgrid which is managed by frequency stability control instead of a commonly-used angle stability control. In [35], the black start unit allocation procedure is solved by examining constraints including thermal limits of lines, overvoltage, and consistency of grid, and the optimization problem is solved by linear programming relaxations.

VI. CONCLUSIONS

In this paper, several aspects of islanding operation due to a rapid expansion and integration of distributed generation into power systems have been described, including control techniques for DG systems, seamless transition between modes, islanding detection techniques, protection, and other functions such as power-sharing and black start capability. The modern power systems continually evolve towards high penetration of inverter-connected generation. From the transmission system perspective, this results in the reduction of system inertia and fault current levels. These changes introduce many challenges to islanding and protection schemes. Specifically, when it comes to islanding detection, the presence of a low inertia, makes it difficult to discriminate between transients resulting from wide area events and genuine islanding occurrences. This effectively highlights that conventional islanding detection schemes (e.g. RoCoF and VS) are no longer suitable. The problem of low inertia is also echoed by the issues related to generator control when it comes to matters of transient stability. With regards to protection, low short circuit levels will make traditional protection schemes unresponsive as limited fault current is produced. It is, therefore, evident that the aforementioned challenges call for further research when it comes to islanding detection, control and protection. Future research should systematically address the challenges outlined in this review paper by seeking innovative solutions such as the potential of coordinated control and protection strategies, the utilization of advanced communication infrastructures, demand-side management, and DG contribution to black start capability.

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